

THE DISCOVERY OF 8.9 SECOND PULSATIONS FROM THE VARIABLE X-RAY SOURCE 2E0050.1–7247 IN THE SMALL MAGELLANIC CLOUD

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ABSTRACT

During a systematic search for periodic signals in a sample of ROSAT PSPC light curves, we discovered ~ 8.9 s X-ray pulsations in 2E0050.1–7247, a variable X-ray source in the Small Magellanic Cloud. The source was detected several times between 1979 and 1993 at luminosity levels ranging from $\sim 5 \times 10^{34}$ erg s $^{-1}$ up to 1.4×10^{36} erg s $^{-1}$ with both the Einstein IPC and ROSAT PSPC. The X-ray energy spectrum is consistent with a power law spectrum which steepens as the source luminosity decreases. We revealed a pronounced H α activity from at least two B stars in the X-ray error circles. These results strongly suggest that the X-ray pulsar 2E0050.1–7247 is in a Be-type massive binary.

Subject headings: binaries: general — pulsars: individual (2E0050.1–7247) — stars: emission-line, Be — stars: rotation — X-ray: stars

1. Introduction

Accreting X-ray pulsars are mainly found in massive binaries containing an OB donor star and X-ray transient activity is fairly common among those systems which host a Be star. The number of X-ray pulsars of this class that are found in the Magellanic Clouds (MCs) is small, but recent ROSAT observations have substantially increased the sample (Hughes 1994; Dennerl *et al.* 1995; McGrath *et al.* 1994). Compared to those in our galaxy, massive X-ray binaries in the MCs are usually characterised by a lower galactic interstellar attenuation in their direction and a better determined, though larger, distance. For three X-ray pulsars in the MCs (SMC X-1, A0538-66 and RX J0059.2-7138) the presence of a soft X-ray component, in addition to the characteristic hard power law with exponential cutoff spectrum, has been firmly established (Marshall, White & Becker 1983; Mavromatakis & Haberl 1993; Hughes 1994; Corbet *et al.* 1995; Campana 1996).

Based on several ROSAT PSPC observations, we report here the discovery of 8.9 s X-ray pulsations from 1WGA J0051.8-7231, a variable X-ray source in the SMC, which was tentatively identified (Bruhweiler *et al.* 1987) with the B star AV111. The X-ray spectrum showed a marked softening when the flux was a factor of ~ 20 below its peak value. We report also the detection of H α activity from AV111 and another B star within the X-ray error circles. Based on its position the latter star provides a more likely optical counterpart than AV111.

2. ROSAT PSPC observations

The Position Sensitive Proportional Counter (PSPC, 0.1–2.4 keV) in the focal plane of the X-ray telescope on board ROSAT observed the SMC field centered on RA = $00^{\circ} 54^m 28^s.7$ and DEC = $-72^{\circ} 45' 36''.6$ (equinox 2000) on 1993 May 9–12 (seq. 600453, 17600 s exposure; Table 1). The brightest source detected within the field was 1WGA J0051.8-7231 at a position of RA = $00^{\circ} 51^m 53^s.3$, DEC = $-72^{\circ} 31' 25''.3$ (uncertainty radius of $\sim 30''$).

The ROSAT event list and spectrum of 1WGA J0051.8-7231 were extracted from a circle of $\sim 1.0'$ radius (corresponding to an encircled energy, EE, of about 90%) around the X-ray position. Out of the 1750 photons contained in the circle we estimated that ~ 100 photons derived from the local background around the source. The May 1993 light curve of 1WGA J0051.8-7231 was first analysed as part of a systematic study aimed at revealing periodicities in X-ray light curves of a sample of ~ 23000 X-ray sources selected from the White, Giommi & Angelini catalog (1994; Israel 1996). The photon arrival times were corrected to the barycenter of the solar system and a 0.58 s binned light curve accumulated. The corresponding power spectrum calculated over the entire observation duration (~ 3.5 d) is shown in Fig. 1a, together with the preliminary peak detection threshold described by Israel & Stella (1996). Significant peaks were clearly detected around $\sim 2.5 \times 10^{-3}$ Hz and ~ 0.113 Hz. While the former peaks are due to the wobble of the pointing direction (~ 402 s period),

the multi-peaked structure around a frequency of 0.1126 Hz is unique to 1WGA J0051.8–7231 (Fig. 1b); the highest of these peaks has a significance of $\sim 6.5\sigma$ over the entire sample of ROSAT light curves analysed. The power spectrum of the window function is shown in Fig. 1c with the same frequency scale as Fig. 1b; the peaks around the central frequency of 0.1126 Hz are the sidelobes due to the satellite orbital occultations. In the absence of a unique phase fitting solution, we determined the best period in each of four consecutive time intervals by using a Rayleigh periodogram (cf. Leahy *et al.* 1983). The average of these periods gave 8.8816 ± 0.0002 s (90% uncertainties are used throughout this letter)⁸. An upper limit to the period derivative of $|\dot{P}| < 3 \times 10^{-10}$ s s⁻¹ (3σ confidence level) was derived. The modulation was fairly sinusoidal, with a pulse fraction (semiamplitude of modulation divided by the mean source count rate) of $\sim 25\%$ in the 0.1 – 2.4 keV band (Fig. 1a). The arrival time of the pulse minima (that we adopted as phase 0) was determined to be JD 2449118.573193 \pm 0.000003.

The PSPC energy spectrum was fitted with a simple power law model (Fig. 2a and Table 2). The best fit was obtained for a photon index of $\Gamma = 1.1 \pm 0.2$ and a column density of $N_H = (8 \pm 3) \times 10^{20}$ cm⁻² (the galactic hydrogen column in the direction of the SMC is $\sim 6 \times 10^{20}$ cm⁻²). The 0.1–2.0 keV unabsorbed X-ray flux was $F_x \sim 2.5 \times 10^{-12}$ erg cm⁻² s⁻¹, corresponding to a luminosity of $L_x \sim 1.2 \times 10^{36}$ erg s⁻¹ for a distance of 65 kpc.

The position of 1WGA J0051.8–7231 was included in several ROSAT PSPC fields observed between 1991 and 1993 (seq. 600195, 600196, 500249n00 and 500251n00). The first observation was carried out on 1991 Oct 8–9 (1700 s exposure). The only detected source compatible with the position of 1WGA J0051.8–7231 is 1WGA J0051.7–7231 (RA = 00° 51′ 47″.7, DEC = –72° 31′ 29″.2, uncertainty radius of 50″; Table 1). The 1991 Oct 8–9 ROSAT event list and spectrum of 1WGA J0051.7–7231 included about 370 photons accumulated from a circle of $\sim 1.7'$ radius (EE of $\sim 90\%$) after background correction. The source count rate was estimated to be $(6.9 \pm 1.5) \times 10^{-3}$ counts s⁻¹ after correction for PSF and vignetting. The photon arrival times were corrected to the barycenter of the solar system and a search for coherent periodicities was then performed in a narrow range of trial periods (8.7–9.1 s) centered around the May 1993 period. No significant peaks were found above the 3σ detection threshold. The corresponding upper limit on the pulsed fraction was $\sim 60\%$. A simple power law model produced an acceptable fit to the spectrum from the 1991 Oct 8–9 pointing (Fig. 2a and Table 2). The best fit parameters were determined to be $N_H = (7 \pm 3) \times 10^{20}$ cm⁻² and $\Gamma = 2.9 \pm 0.8$. The corresponding 0.1–2.0 keV unabsorbed flux was about $F_x \sim 1 \times 10^{-13}$ ergs cm⁻² s⁻¹, converting to a luminosity of $L_x \sim 5.0 \times 10^{34}$ erg s⁻¹.

In the remaining four ROSAT PSPC observations the source was not detected and only upper limits on the count rates were determined (see Table 1 for details). In the ROSAT All Sky Survey (RASS) the region around the source was observed on 1990 Oct 22–26 (667 s exposure). The source was not detected (2σ upper

⁸This value and error revise the preliminary ones reported by Israel *et al.* (1995).

limit of 1.1×10^{-2} cts s $^{-1}$; cf. Kahabka & Pietsch 1996).

3. Einstein IPC observations

The SMC was extensively surveyed with the Einstein Observatory. The position of 1WGA J0051.8–7231 was included in three Imaging Proportional Counter (IPC, 0.15–4.5 keV) sequences (593, 6755 and 7988). These pointings were analysed in detail (Seward & Mitchell 1981; Bruhweiler *et al.* 1987; Wang & Wu 1992). Two Einstein sources with compatible positions were detected within the ROSAT error circle of 1WGA J0051.8–7231: 2E0050.1–7247 (seq. 6755, source # 27 of Wang & Wu 1992) and 2E0050.1–7248 (seq. 7988, source # 3 in Bruhweiler *et al.* 1987). In the following we will use only the designation 2E0050.1–7247. The count rate of 2E0050.1–7247 increased by a factor of ~ 5 from 1980 Apr 15 (seq. 6755) to Apr 20 (seq. 7988, Table 2; Wang & Wu 1992). Correspondingly the hardness ratio underwent a significant increase. The source was not detected in sequence 593 (upper limit of $\sim 2 \times 10^{-2}$ cts s $^{-1}$; Wang & Wu 1992).

We reanalysed the Einstein IPC sequences 6755 and 7988 to search for the 8.9 s periodicity. The IPC event lists were extracted from a circle of $\sim 1.6'$ radius (corresponding to an EE of $\sim 90\%$) around 2E0050.1–7247 and contained, respectively, ~ 300 and 100 source photons. The arrival times of the 0.15–4.5 keV photons were corrected only for the earth motion; the search for coherent periodicities was then performed over the ~ 8.65 – 9.15 s period range. No significant periodic signal was detected (upper limit of $\sim 75\%$ and $> 100\%$ for sequence 6755 and 7988, respectively). We fitted the IPC spectra with a power law model, keeping N_H fixed at 8×10^{20} cm $^{-2}$ (the best value obtained with the ROSAT PSPC in May 1993). The derived photon index is in both cases consistent with $\Gamma \sim 1$ (large uncertainties are due to poor statistics; Table 2). The inferred 0.15–3.5 keV unabsorbed luminosities were $L_x \sim 1.4 \times 10^{36}$ and $\sim 3.1 \times 10^{35}$ ergs s $^{-1}$ for sequence 6755 and 7988, respectively.

4. Optical Observations

The Einstein error circles of 2E0050.1–7247 include the optical position of AV111 ($< 40''$ offset), a variable B1 giant in the SMC, that was tentatively identified as the optical counterpart (Bruhweiler *et al.* 1987; Wang & Wu 1992). In order to reveal the H α active stars in the Einstein and ROSAT error circles ($\sim 40''$ and $\sim 30''$ radius, respectively), we obtained three $\sim 4' \times 4'$ images centered on AV111 with the ESO–La Silla Dutch 91 cm telescope on 1996 Aug 12–13. The exposure time was 90, 120 and 900 s for the V, B and H α frames, respectively. Comparing, for each object in the X–ray error circle, fluxes in the B, V and H α bands, we found several H α bright stars. In particular, the two most prominent were AV111 itself and a previously unclassified star (hereafter Star1) at an optical position R.A. = $00^{\circ} 51' 56''.6$, DEC = $-72^{\circ} 31' 30''.0$ (uncertainty $< 10''$; see also Kahabka & Pietsch 1996). While consistent with the Einstein IPC error circles ($\sim 40''$ radius), the

position of AV111 was determined to lie $\sim 10''$ outside the ROSAT PSPC error circle ($\sim 30''$ radius; Fig. 3). On the contrary the position of Star1 is well within the PSPC error circle. The magnitude ($V \sim 13.4$) and the color ($B-V \sim -0.28$) were also compatible with those of a B giant at the distance of the SMC.

A medium resolution spectrum of AV111 was also taken on August 13, 1996 (600 s exposure) with the ESO–La Silla 1.5 m Spectroscopic Telescope. The spectral range and resolution were $\sim 4950 - 6950 \text{ \AA}$ and $\sim 1 \text{ \AA}$ (at 6500 \AA). A pronounced $H\alpha$ emission feature was apparent in the spectrum with an equivalent width of $5.4 \pm 0.5 \text{ \AA}$. We determined a line centroid to be at 6566 \AA corresponding to a radial velocity of $\sim 150 \text{ km s}^{-1}$ (the SMC line of sight velocity is $\sim 168 \text{ km s}^{-1}$). Two distinct components with comparable intensities could be easily distinguished close to the line centroid. These were peaked at 6564 and 6569 \AA respectively, corresponding to a velocity difference of $\sim 200 \div 250 \text{ km s}^{-1}$.

5. Discussion

The 8.9 s pulsations from 2E0050.1–7247 together with the probable identification of an $H\alpha$ emitting counterpart strongly suggest that the X-ray source is an accreting magnetic neutron star likely in a Be star X-ray binary. The X-ray source was detected over a range of $0.1\text{--}3.5 \text{ keV}$ luminosities from $\sim 5 \times 10^{34}$ to $\sim 1.4 \times 10^{36} \text{ ergs s}^{-1}$; on other occasions the source remained undetected, with upper limits that in two cases were just below the minimum detected luminosity. These large variations are suggestive of a transient behaviour.

The relatively low peak X-ray luminosity detected from 2E0050.1–7247 indicates that the source was observed either during the decay (or the rise) of a large outburst or during a lower luminosity (possibly recurrent) outburst. Increased $H\alpha$ emission from AV111 or the other candidate (Star1) could provide a useful indicator of resumed X-ray activity from 2E0050.1–7247 (this might be also useful to confirm the association of either candidates to the X-ray source). Based on the orbital period / spin period correlation found by Corbet (1984) for Be star X-ray pulsars, the orbit of 2E0050.1–7247 should be in the $\sim 30 \text{ d}$ period range.

Despite the limited energy range, the power law spectral slope of 2E0050.1–7247 measured by ROSAT when the source luminosity was $\sim 10^{36} \text{ ergs s}^{-1}$ ($\Gamma \sim 1$) is similar to that of most accreting X-ray pulsars. A substantially softer spectrum ($\Gamma \sim 3$) was measured when the source luminosity was $\sim 5 \times 10^{34} \text{ ergs s}^{-1}$. A clear spectral evolution was observed in the outburst decay of a sample of transient X-ray pulsars, such as V0332+53 (Makishima *et al.* 1990) and EXO2030+375 (Reynolds, Parmar & White 1993). However in these cases the lowest detected luminosities were substantially higher ($\approx 10^{36} \text{ ergs s}^{-1}$) than in the case of 2E0050.1–7247; this suggests that their neutron stars were further away from the regime of centrifugal inhibition of accretion which occurs close to the end of a transient X-ray pulsar outburst (Stella, White & Rosner 1986). By requiring that the centrifugal barrier is open for an accretion luminosity of $\sim 10^{36} \text{ ergs s}^{-1}$ we derive an upper limit of $B < 1.5 \times 10^{12} \text{ G}$ to the magnetic field of the neutron star in 2E0050.1–7247. For a

spin period of 8.9 s the luminosity gap across the centrifugal barrier should be a factor of ~ 700 (Corbet 1996), indicating that when the source was a factor of ~ 20 fainter the centrifugal barrier could not be completely closed and accretion onto the neutron star still took place. The case of 2E0050.1–7247, together with that of the other X-ray pulsars discussed above, suggests that the production of very soft X-ray spectra results (for some yet unknown reason) from the accreting neutron star approaching the regime of centrifugal inhibition of accretion.

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Fig. 1.— Power spectrum of the 0.1–2.4 keV ROSAT PSPC light curve of 1WGA J0051.8–7231 (panel *a*). The preliminary 3σ detection threshold is also shown. Peaks around multiples of $\sim 1.7 \times 10^{-4}$ Hz and $\sim 2.5 \times 10^{-3}$ Hz are spurious (see text for details). The peaks around 0.113 Hz revealed the presence of a 8.9 s periodic signal in 1WGA J0051.8–7231. The latter peaks are shown in greater detail (panel *b*) together with the power spectrum of the window function (panel *c*) Folded light curves at the best period of 8.8816 s are shown as an insert in panel *a* for two different energy ranges.

Fig. 2.— ROSAT PSPC spectrum of 1WGA J0051.8–7231 during the 1993 May 9–12 and 1991 Oct 8–9 observations (upper panel). The best fit power law models are shown, together with the corresponding residuals. The lower panel gives the 1, 2 and 3σ confidence contours in the $N_H - \Gamma$ plane for the 1993 May 9–12 (solid lines) and 1991 Oct 8–9 spectra (dash-dotted lines). The crosses indicate the best fit values. The vertical line represents the estimated galactic hydrogen column.

Fig. 3.— ROSAT PSPC image of the SMC region around 2E0050.1–7247 / 1WGA J0051.8–7231. The ROSAT and Einstein best positions are given (crossed circles), together with their error circles ($\sim 30''$ and $\sim 40''$, respectively). The filled circles indicate the optical positions of AV111 and the previously unclassified B star (Star1).

Table 1: ROSAT PSPC observations of 2E0050.1–7247

Start Time		Stop Time		Seq. (#)	Exp. (s)	Count Rate (10^{-3} cts s $^{-1}$)
91 Oct 8	03:10	91 Oct 9	02:38	600195	16981	6.9 ± 0.5
91 Oct 10	03:06	91 Oct 10	04:47	600196	1346	< 30 ^(a)
92 Apr 10	15:30	92 Apr 25	16:41	600196	22680	< 5 ^(b)
92 Apr 17	17:01	92 Apr 27	16:28	600195	9651	< 10 ^(c)
93 May 9	07:17	93 May 12	20:14	600453	17599	114 ± 3
93 Nov 5	23:21	93 Nov 9	02:37	500249	19262	< 20 ^(d)
93 Nov 30	05:39	93 Nov 30	07:37	500251	2093	< 60 ^(e)

^(a) The wobble direction was such that the source was almost always obscured by a rib.

^(b) As a result of the wobble the source was obscured by a rib for $\sim 50\%$ of the time.

^(c) The wobble direction was such that the source moved parallel to the rib $\sim 1'$ away from it and therefore was unobscured.

^(d) As a result of the wobble the source was obscured for $\sim 25\%$ of the time.

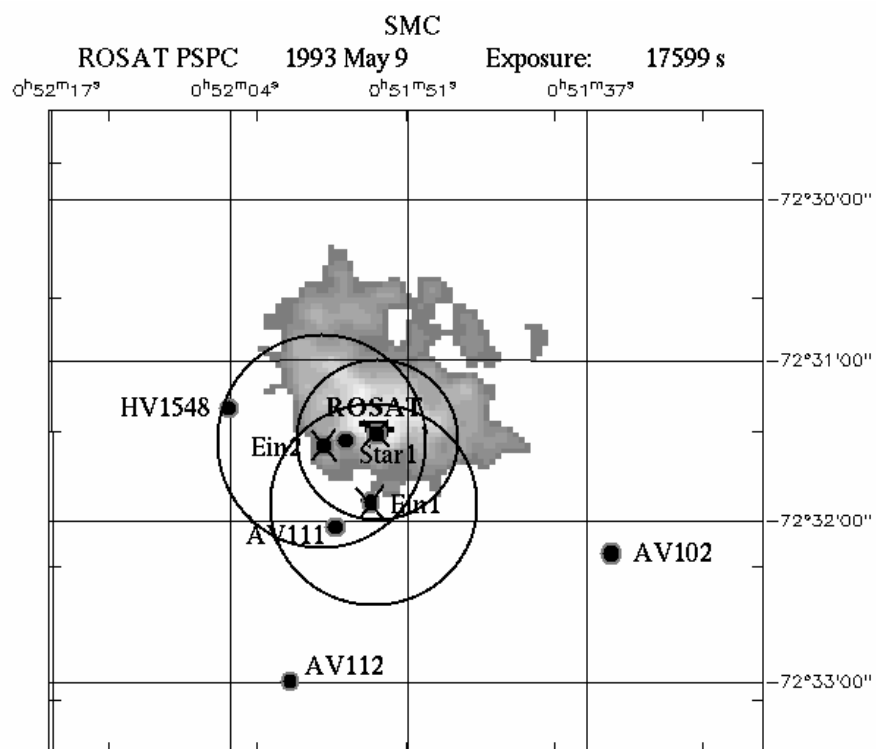
^(e) The wobble was such that the source spent $\sim 90\%$ of the time under a rib or out of the field of view.

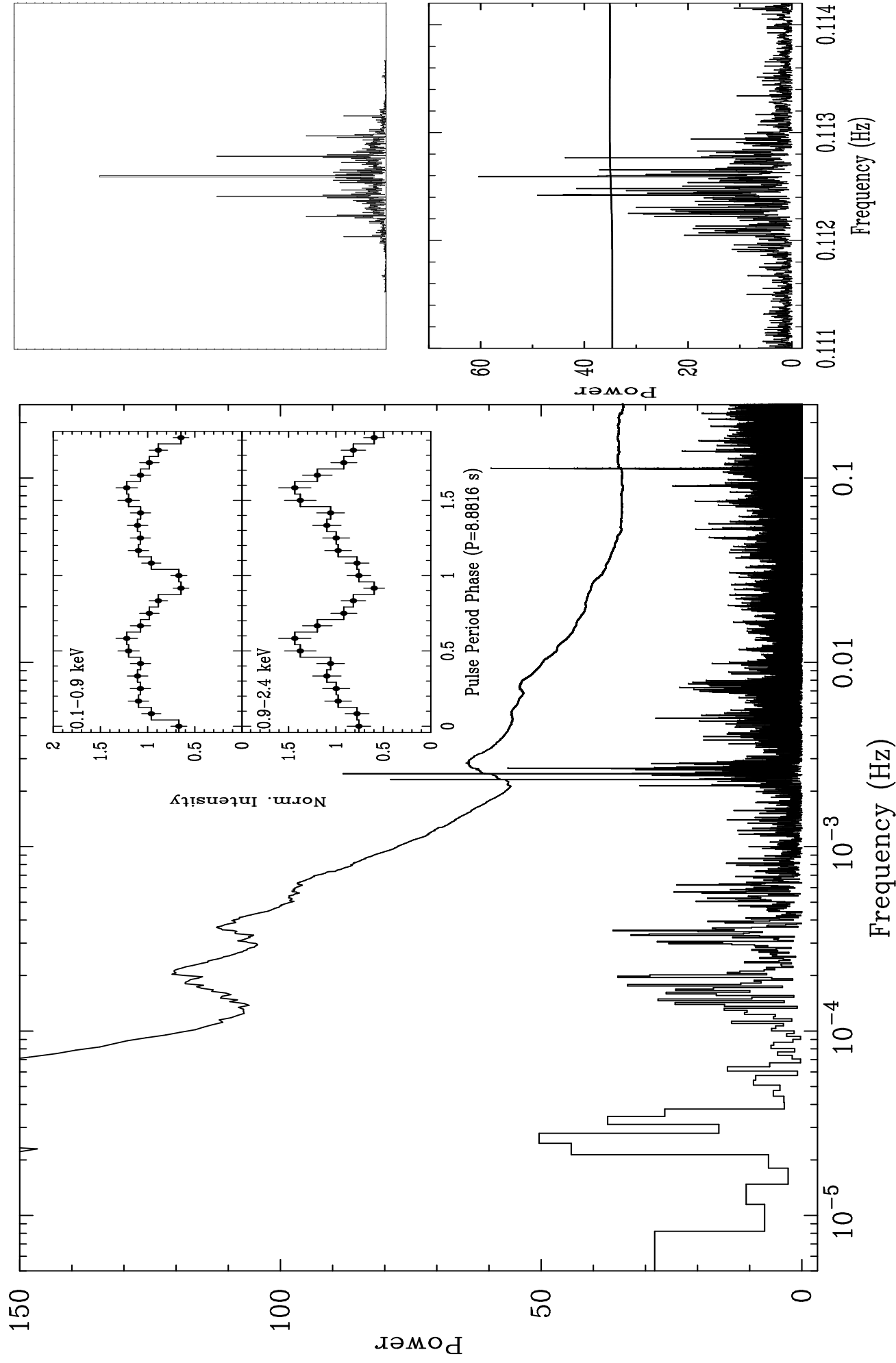
Table 2: ROSAT PSPC and Einstein IPC Spectral Results for 2E0050.1–7247

Parameter	Seq. (#)	ROSAT PSPC		Einstein IPC	
		600453	600195 ^a	6755	7988
N_H (10^{20} cm ⁻²)		$8 \pm_2^3$	$7 \pm_3^9$	8 (fixed)	8 (fixed)
Γ		1.1 ± 0.2	$2.9 \pm_{0.7}^{0.8}$	0.9 ± 0.9	$1.0 \pm_{0.9}^{1.1}$
F_x (10^{-12} erg s ⁻¹ cm ⁻²)		2.5	0.1	3.4	0.7
Count rate (10^{-3} ct s ⁻¹)		114 ± 3	6.9 ± 0.5	70 ± 10	16 ± 1
L_x (10^{35} erg s ⁻¹ , d=65 kpc)		12	0.5	14	3.1
Reduced chisquare		1.1	1.0	0.6	0.5

^aOct 1991 data only.

Note. — X-ray fluxes and luminosities are unabsorbed and refer to the 0.1–2.0 keV and 0.15–3.5 keV band for the ROSAT PSPC and Einstein IPC, respectively. Quoted uncertainties are 68% confidence for one parameter of interest.





Start Time 1072 10:27:27:386 Stop Time 1075 23: 6:22:670

